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MODERGIS application: Integrated simulation platform to promote and develop renewable sustainable energy plans, Colombian case study

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ABSTRACT

This research presents the MODERGIS Integrated Simulation's Platform as a tool to promote and develop renewable energy plans under sustainability criteria, in order to increment the participation of renewable technologies in the national "energy mix" and shows an application to Colombia as a case study. Potential zones of solar and wind energy and productive areas were determined for bio-energies, by means of a geographical information system which simulated energy scenarios influenced by climatic phenomena up to the year 2030. Results yield potentials of 26,600 MW in wind energy and 350,000 MW in solar energy. Bioenergy potentiates in a sustainable way of 366,310 km per biomass, 291,486 km in African palm, 9,667 km in sugar cane. These scenarios were simulated in a supply/demand with time horizons up until 2030, including an analysis of the effects on the energy systems of the El Niño Southern Oscillation atmospheric component (ENSO). Finally, in order to obtain an appropriate mix of renewable sources that could be introduced in the national energy mix, the Multi-Criteria Analysis method VIKOR was used, allowing to perform performing 5151 possible combinations of renewable projects; the optimal selection corresponds to 600 MW from wind power, 740 MW solar photovoltaic and 660 MW solar thermoelectric. Giving these results to the new scene allowed for incrementing the participation of renewable technologies up to a 0.23% in the current year and up to a 7% of the "energy mix" in the year 2030.

Contents

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1. Introduction

Adequate and reliable energy supply is an essential element of sustainable development. Energy is vital for poverty's eradication and for human well-being improvement. Many regions of the world do not have reliable energy; moreover, the economic limits of its usage are exceeded. In other areas, the pressure and degradation caused by the environment prevents sustainable development preservation. Nearly 1.4 billion people still lack access to electricity (87 percent of whom live in rural areas), and one billion has access only to untrusted networks of electricity. It is estimated that the capital investment needed to provide modern energy services to this population is on the order of $40 billion dollars per year until 2030. This represents about three percent of the total investment in energy worldwide that is expected for this period [1].

The current energy model, based on fossil fuels, has enabled great scientific and technological achievements; therefore, it has enabled global economic development. At the same time the planet's living conditions have deteriorated progressively and irreversibly. As demonstrated in Barcelona's 2004 forum the current energy model is unsustainable if it continues with the same patterns of energy consumption and maintains dependence on fossil fuels, it is recommended to extend the investigations about the energy development based on new renewable and sustainable sources that not only continues feeding the developing motor, but also contributes to a better quality of life for future generations [2].

One of the initiatives in this field is being elaborated by researchers from Stanford and California Universities. They state that it is possible to offer clean [3], perpetual and possible conversion of energy at low costs with an increment on the energy efficiency. Researchers determined that 3.8 million wind turbines of 5 MW will be needed (50% of energy demand), 49000 plants for solar concentration of 300 MW (20% from the energy demand), 40000 photovoltaic plants of 300 MW (14%), 1.7 billion of individual solar panel systems of 3 kW (6%), 5350 geothermal plants of 100 MW (4%), 270 new hydroelectric projects of 1300 NW (4%), 720000 wave generators (1%) and 490000 tidal turbines of 1 MW (1%) for supplying the energy demand within all sectors and uses in the year 2030 with this new system called WWS [4].

While several countries agree on the need of renewable energy, several policy mechanisms have been developed to foster it, such as Feed-in tariffs and standard portfolios [5], Then new models are needed to identify the available renewable resources, and decide which projects to develop in order to obtain an optimum energy mix that combines economic and environmental [6] criteria.

G. Caspary has assessed the competitiveness of the different forms of renewable energy in Colombia for the next 25 years, comparing the cost of energy production for a set of renewable energy sources, and the likelihood of them long-term cost of energy traditional [7]. Although the article does not treat the problems of generation in isolation but considers welfare issues regarding environmental and social impacts of different technology options, contemplates the costs of externalities and left free to discuss broader issues of welfare, and this does not depend on the choice of technologies, but rather the regulatory environment for the provision of access to energy [8], which will be based depending on the potentiation of the renewable resource [9]. It is clear that the institutional framework and the aspects of policy consideration and regulation must be sufficiently strong and consistent to the results of this model for that can be implemented in a structured and articulated [10].

The authors of this paper propose MODERGIS as a new model that helps to integrate renewable energies in a flexible way, assessing simultaneously the energy potential in time and territory of energy supply and demand in a specific geographical area. In addition it is coherent with the use of integrated tools for assessing renewable energy [11]. It has a virtual interphase that includes three interconnected modules. The first module is named ENERGIS; it is based in Geographic Information Systems (GIS), and allows estimating the potential of renewable energy resources in a region through regional geographic information.The treatment method or technique of geographic information allows to efficiently combine basic information to obtain derived information. There is a set of tools (hardware and software) that facilitates the implementation of these activities [12].

A second module is feed with this information, named ENERDEM, based on a supply/demand model, of the Bottom Up type denominated Long-Range Energy Alternatives Planning System (LEAP) [13] it has been widely used for estimating costs of reduced potential energy consumption, associated with the reduction of CO^2 emission, through the use and management of energy's efficiency. It is characterized because it does not require time series, it estimates the aggregate demand for energy, not only produces an energy balance but also calculates the emission of greenhouse gases, applying the methodology from Intergovernmental Panel on Climate Change (IPCC) [14], which permits energy scenery simulation, in this case under climate phenomena conditions and projecting demand and future energy requirements. Subsequently, different conflicting criteria are evaluated in order to make decisions of social, environmental and economic character, determining its feasibility.

This test is processed by the third module ENERSOS, documented in the Multicriteria Analysis and Multi-Objective which are used in planning and decision making process of energy supply, as essential elements for sustainable development, but complex interactions can hinder the proficiency of these tasks. The decision multi-criteria analysis (DMCA) provides methods to mitigate this difficulty and for this it has been used by decision makers through a long time [15]. The DMCA is a form of integrated sustainability assessment, adequate to address complex problems with a high degree of uncertainty, conflicting objectives and multiple interests and perspectives. Traditional approaches from a single criterion are intended to identify options for greater efficiency at lower costs; however, from the mid-80's with the environmental awareness gradually altered the structure from the analysis model of one criterion. In actuality, the focus on environmental protection has turned the DMCA in a helpful tool for power systems [16] and applied with other systems of social, economic, agricultural, industrial, ecological and biological [17].

This research selected the method Vikor (VlseKriterijumska Optimizacija I Kompromisno Resenje) that was developed by Serafim Opricovic as a multi-criteria analysis method for optimization of complex discrete systems with conflicting and incommensurable criteria [18]. This method focuses on ranking and selecting the best solution from a set of alternatives in the presence of conflicting criteria. One of the main advantages that

VIKOR offers is the possibility of determining a compromise solution, meaning, the closest to ideal, reflecting the position of most decision makers involved [19], within the platform programed algorithm that systematizes the procedure and makes it more adaptable and feasible in the simulations.

This paper presents the application of the Modergis for potentiation of renewable energy in Colombia as a case study, analyzing supply and demand of energy resources, the composition of energy mix and the involvement of environmental, social and economic in making decisions to include renewable energy in national energy plan by 2030.

2. MODERGIS Definition

MODERGIS is a comprehensive tool that searches the integration of renewable energy, simultaneously evaluating the special and temporal energy potential of supply and demand of energy in a geographical area. Furthermore, it is coherent and consistent with the use of integrated and flexible model tools for the assessment of these resources [11]. It includes the integration of geographical information systems - GIS [20], to identify and estimate potential renewable resources of energy, a model of the type Bottom Up, LEAP that allows the simulation of energy demand and supply [21], and finally the Decision Multi-Criteria Analysis VIKOR method that evaluates a set of energy alternatives under the criteria of sustainability [22]. These tools integrate the economic, social and environmental dimensions of great importance in our environment and that are imperative for the evaluation and decision-making in the energy planning.

The methodological procedure for the application of the MODERGIS model is based on the integration and correlation of three modules that comprise, ENERGIS, ENERDEM and ENERSOS (Fig. 1), and will be not only applied in the Colombian case study, but also could be applied in any region of the world as long as they have the required information.

2.1. Renewable energy potential identification – ENERGIS

ENERGIS is a virtual environment that allows the spatial analysis of a geo-referenced place through Geographic Information Systems. This analysis will make it possible to visualize and estimate the potential energy resources in the area of study, according with the data restrictions entered into the background. It begins by mapping information based on national interest, for this research the Instituto Geográfico Agustín Codazzi (IGAC) [23] was in charged with data regarding the departments, municipalities, urban centers, forest reserves, national parks, rivers and large surfaces of water, wind and solar radiation atlas. This data establishes, first, a framework for analysis and spatial reference, second, some initial restrictions, referring to those zones where it is not possible to develop energy projects. The emphasis is the renewable resources potential evaluation (primarily solar, wind, wood energies and biofuels), anticipating the increase of the "energy mix" in potentially attractive areas for inclusion or replacement by new forms of energy.

ENERGIS uses spatial data of raster type represented by cells or pixels of homogeneous units of information of 500 by 500 m, which exhibits various differences with the vector model given the discreet way to represent spatial data [24]. This provides a more in-depth treatment of thematic data, allowing the possibility of applying algebra maps and relationships of Boolean logic and arithmetic, such as the possibility of multivariate classifications, univariate and multivariate statistical operations, operations of immediate vicinity and other possibilities such as interpolations [25].

Having the compilation phase defined and organizing information, unification of spatial references, parameterization of cell sizes and output of the analysis, proceeds to model the variables and phenomena associated to the problem of the study, namely the identification of potential areas for the development of sustainable energy sources based on biofuels (African Palm, sugar cane, jatropha, corn and banana) and wood energy (sustainable firewood), as well as in the potential for solar and wind energy.

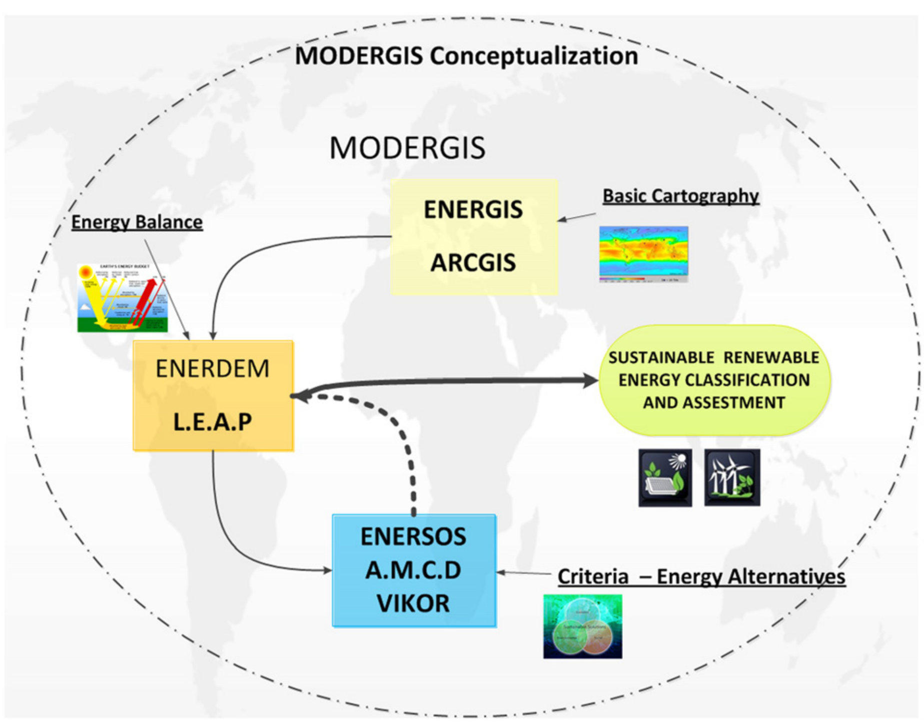


Fig. 1. MODERGIS Conceptualization.
Source: ModerGIS.

In order to determine restrictions, the process of elimination and selection of the best alternatives, the use of models was necessary from which its results ensures that action will be given only in those places in which the restrictions are respected. A template is generated in which the possibility for the potential of sustainable energy projects is analyzed, excluding those areas which by economic, ecological or regulatory interest may not be used by such projects. In this sense, urban areas, water surfaces, moorland protection areas, areas of natural reserves, the territories inhabited by indigenous and Afro-descendant communities and involvement of the second law of forest reserves are excluded. The merger of these areas constitutes a boundary for subsequent analyses, which in conjunction with national borders will define the area of analysis [26].

The procedure to identify the feasibility of promising energy crops for biofuels, were defined by the following selection criteria: Altitudinal Floor, precipitation, soil quality, proximity to land and railway tracks, power grids and pipelines. For each crop the soil quality was evaluated, as deep, permeable, soils with good nutrients availability, good water capacity, free from flooding or water retention, small slope, loamy texture, pH, temperature and height above sea level. Given that results are in a macro scale, it is not possible to determine a coincidence of detail in all conditions; but if a regionalization of the feasibility where the criteria that makes the presence of the event possible converge.

Once the sources of information that define the spatial distribution of the practicality to develop a source of biomass-based fuels are obtained, it is followed by the generation of queries that will show how many surface units are within a particular source in a department. This operation is done through recurring operations (for each source), spatial statistics using as matrix to the map of energy source and as the template for consultation to the map of polygons that define the departments. This procedure reports the main statistics of the cells that are contained in the polygon borders, applying the equation of the total cell number as the value in units (meters) of each cell and relating its value with the resulting unit.

2.2. Scenario supply-demand simulation ENERDEM

The second block called supply and demand energy ENERDEM, is supported by the Bottom-UP LEAP model type, which is based on detailed approximations for the energy demand, supply and expansion including options for increasing efficiency and simulation in the processes. This model has been used extensively to estimate costs from the potential energy consumption reduction, associated with the reduction CO_2 emissions, through the energy efficiency use and management.

It is characterized because it does not require time series, it estimates the accumulate demand for energy, predicts the transformation of energy needed, determines the supply of energy resources, and not only produces an energy balance but also calculates the emission of Greenhouse Gases GHG, applying the Intergovernmental Panel on Climate Change (IPCC) methodology [27].

LEAP is a tool that can be used to create models of different power systems, where each requires its own data structure. Supports a variety of different modeling methodologies demand the range is from Bottom-Up (counting techniques of energy end-use) to top-down (macro modeling). The power supply provides a range of methodologies for counting and simulation are powerful enough to model and expansion plans of generation capacity in the electricity sector, which in turn are sufficiently flexible and transparent to allow the incorporation of data and results of other more specialized models [13].

The LEAP modeling capability operates at two levels basic conceptual. At the first level, manages the built-in calculations of energy, emissions and cost effectiveness. In the second level, the user enters expressions that can be used to specify variables over time or create a wide variety of sophisticated multivariable models, while enabling the econometric and simulation approaches for inclusion in its accounting structure.

2.3. Renewable energy Alternatives selection and combination – ENERSOS

ENERSOS internal structure is based on the Multi-Criteria Decision Analysis method VIKOR, which optimizes complex discrete systems with conflicting and immeasurable criteria [28]. This method focuses in ranking and selecting the best compromise solution, meaning the closest to the ideal solution, starting from a set of alternatives in the presence of conflicting criteria reflecting the position of the majority of decision makers involved.

This module is divided in two stages: the first stage corresponds to the solution of a problem of Multi-Attribute decision analysis; it is given a set of options and a set of criteria to evaluate, with these a payoff matrix is built, from where the data to make the calculations will be extracted. The result of this module is a hierarchical list that is achieved by the comparing each option while taking into account a number of criteria, here called attributes, which describe the performance of these alternatives in several aspects, compared according to the decision maker's preference.

The second stage is organized as a continuation or annex of the first stage and it is based on the solution for a multi-objective problem [29]. The delivered data are the best three chosen alternatives by the first module and a set of restrictions that the program must compute, through an algorithm, from all possible combinations that represent real projects, to meet the main constraint. After finding this set of combinations, an objective set of functions are given where different alternatives are evaluated and finally a similar method to that used in the first module will be used but with a multi-objective adaptation [30]. The information given to the VIKOR method is provided by the user based on the technologies and market prices [4], [31]. It abides a set of alternatives to achieve the desired goal, and a set of criteria to evaluate the different performance aspects of these.

3. Colombian CASE STUDY

Colombia, a bidding country in energy, counts with significant coal reserves, limited petroleum and natural gas reserves. According the Solar and Wind Energy Resource Assessment (SWERA) (http://swera.unep.net/) and the European Photovoltaic Industry Association (EPIA) (http://www.epia.org/), Colombia is located in a strip where the provision of renewable energy resources is promising. Optimizing the nation's energy options is a fundamental exercise to amplify the range of alternatives and natural resources that make up the country. Moreover, while the country is a modest source of greenhouse gas emission, it is very consistent with the necessity of establishing an energy development under the carbon emissions, due to the vulnerability to the impact caused by global warming according to the reports from The Integrated National Adaptation Project from The World Bank [32].

The key issue is the vulnerability of water resources to climate change and the presence of several droughts when El Niño Southern Oscillation (ENSO) occurs, due to the high share of hydropower in the energy mix. Complementary actions should be taken to avoid shortages of water for human consumption and energy in the Caribbean and Andean regions, reason to raise the cost of provision, and in some cases, it may cause conflicts because of their use [33].

The participation of alternative energy resources in Colombia is meaningless, only 0.23% of the total electricity generation is wind power. Therefore, several elements are urgent and necessary to measure the potential, quantify the exploitation volumes and analyze the scenarios for energy exploration, identifying which ones will be the best and optimal, ensuring a reliable energy supply and searching for equilibrium in the participation of alternative renewable energy in the energy matrix.

Colombia has great energy resources. Natural gas reserves in 2008 were 7.3 Tera cubic feet (from which 60% were proven reserves). Petroleum reserves are much more limited and can be insufficient to maintain self-sufficiency in short term. At the end of 2009, the proven petroleum reserves were 1988 million barrels, self-sufficiency for nearly seven years [34]. Similarly, coal reserves are evaluated in about seven billion tons (or about a hundred years of production at the current extraction rate) the Unidad de Planeación Minero Energética (UPME). [35]. Colombia also has considerable potential, relatively low-cost hydroelectric power as a result of its location in the inter-tropical convergence zone and its mountain ranges.

In this frame of reference, Colombia depends largely on its hydroelectric capacity which provides around 67% of the generated energy. In 2008, the installed capacity was 13.5 GW to form a matrix of 67% in hydroelectric, 27% in natural gas, 5% coal, 0.3% wind and cogeneration 0.7%. The total energy demand in the same year was 54 TWh, which represents one of the lowest carbon emissions in the region [35] due to the high share of hydroelectricity.

Climate variability impact, such as the El Niño Southern Oscillation ENSO [36], creates uncertainty in the hydrological inputs to the reservoirs, reason why Colombian electricity sector would be predestined to permanent rationing [37]. For this reason alternatives should be presented to diversify the energy generation matrix, since the thermic capacity installed only participates in about 20% of the total capacity for the year 2018. Resorting to other generative sources is necessary as the national Generation Expansion Plan (Plan de Expansión de Generación) 2010–2024" [38] mentions.

Colombia has been characterized to have environmental conflicts in some energy projects, generating problems to the ecosystems and communities that are located in the areas of influence for energy projects. This is reflected on the over expenditure for the projects and irreparable damage to the environment and the affected population [39]. Due to this notion it is important to modify the "energy mix" structure towards the less harmful vectors, using comprehensive evaluation procedures that minimize the impacts to natural and social biodiversity wealth, characteristics of a multiethnic and multicultural country [40].

In order to implement a sustainable energy model for Colombia, it is necessary to have diverse planning tools that allow to include in its method the dimensions of sustainable development (social, economic and environmental), in order to allow a comprehensive evaluation of alternatives from all aspects that characterize a society. Using these tools can determine the energy needs of a specific geographic area; maximize new energy resources that can be included in a sustainable "energy mix" and comprehensively evaluate the energy technologies with the same pattern, all aimed under the sustainable development criteria. These tools are available separately [11], and to achieve the goal of fully evaluating an alternative integrally [22], an individual analysis has to be done, which consequently would enable a comprehensive global analysis of the results. This is a complicated task due to the large amount of data that is necessary to manipulate. MODERGIS is a last generation tools that facilitate energy planning processes aimed at promoting renewable energies, determining the most appropriate option or options to be selected.

4. MODERGIS application to the case study

4.1. Renewable energy potential identification – ENERGIS

The study area was the mainland of the Republic of Colombia, located from 4° 13′ 30″ south latitude to 12° 27′ 46″ north latitude and from 66° 50′ 54″ west of Greenwich and 79° 0′ 23″ east of the same meridian. The boundary lines are representative to the North with the Republic of Panama and the Caribbean Sea, to the East with the Republics of Venezuela and Brazil, to the South with Peru and Ecuador, and to the West with the Pacific Ocean. Colombia has 1.141.748 km^2 of continental surface, coupled with marine and submarine waters it extends to 2.070.408 km^2. As a spatial reference for the analysis, is based on the Universal Transverse Mercator System UTM, originating from the Bogota Observatory coordinates and measured in meters [23].

4.2. Scenario supply-demand simulation ENERDEM

For the Colombian case study, 2005 was taken as a reference and updated with the available information for the year 2008 such as: energy balances and statistical information of demand, supply and electric power generation, information the UPME. Socioeconomic information was established from basic population statistics, gross domestic product and economic indicators from the Departamento Nacional de Planeación (DNP) and the Departamento Nacional de Estadistica (DANE). With the energy and economic figures proceeded to establish the energy intensities, defined as the relation between energy consumption from the energy sector *i* and the added-value or the production value of the economic sector *j*. Time horizon was fixed until the year 2030, with results every two, five and ten years, searching to be coherent with the official figures from the government agencies.

4.2.1. Energy demand

For the five defined sectors from the UPME energy balance the tree structure is establish and extended to lower levels, always with the prospective of establishing scenarios to simulate the access to new energy alternatives, in this case renewable energy.

Residential sector includes the urban and rural. It is considered that by the year 2030 a change among the rural and urban participation will change, urbanization processes being dominant from 74.1% in 2005 to 79% in the year 2030. The energy activation of rural areas will change from 73.5% to 90% in the year 2030. It simulates that a 50% solar energy will be implemented in non-electrified rural households with this source.

Industry sector includes eleven subsectors according to the Unified International Industry Coding (CIIU) to three digits. An improvement in electric motor efficiency is proposed from the 80% to 90% and in some cases coal for natural gas substitution, where it is feasible.

Transport sector includes the public and private road network and other transportation ways. A the simulation for road network transport sector goes with biofuel blends of gasoline with E10% ethanol and for diesel B 5% with palm oil, including the potentiation results of crops by ENERGIS. According to the penetration of these technologies Hybrid electric fuel cars are included.

Agriculture sector includes crop planting activities and mechanization of the same. It sets out the guidelines of the plan for energy's rational use (PROURE), with a goal of 10% reduction in electricity consumption by 2030.

Commercial sector includes official and public. Natural gas will have participation in between 11% to 20%, and by the year 2030 a gradual reduction in the electric energy from 58.9% to 45% expected according to the plan for the rational use of energy.

4.2.2. Energy transformation

Necessary primary energy transformations are analyzed to produce secondary energy. A report of the resources and energy production Colombia possesses is delivered according to: petroleum, natural gas, mineral coal, biomass and firewood; crude oil refining capacity and production its derivatives, electric power generation with hydroelectric and thermoelectric plants, wind power, solar and other sources, generated by auto producers and co-generators.

In hydrocarbons, refining capacities of about 244000 barrels per day are taken into account. In electricity the total generating capacity of 13456 MW, 6540 thermal and 8640 hydro is contemplated. The entry of new power plants is simulated with an energy production of 3069.3 MW hydro and 351 MW thermal, contemplated in the obligation of energy auctioned by the UPME between the years 2014 and 2019. This scenario is characterized by simulating electric energy supply, recognizing the growth in demand, but for the first time it includes the effect of climatic *El Niño* Southern Oscillation ENSO, the expansion plan, given the projects from the Expansion Plan 2009–2023 Reference UPME high hydroelectric component. The scenario from the Instituto de Hidrología Meteorologia y Estudios Ambientales (IDEAM) studies of Colombia in the 2010 [41] is in inferred, Poveda y Mesa, (1996), Carvajal, (2003), Pabón (2007), on current and periodic occurrences observed in recent decades, ranging from nine (9),six (6) and three (3) years. For the case study scenario, the most critical of three years and average of 10 to 12 months is assumed for the LEAP MODERGIS, starting with 2010 and making cuts and simulations until 2030.

4.2.3. Power supply

Renewable energy potential or reserves is the innovation that this modeling has due to the obtained results for the first time from the ENERGIS, characterized because they maintain the criteria of sustainable energy distributed throughout the national territory. The gathered data is 26.6 GW in wind power, 350 GW in solar power and the usable areas of 68 066 Km^2 for biomass, 291 486 Km^2 African Palm, 710 619 Km^2 of Jatropha and 9 6687 Km^2 in sugar cane.

All the proven reserves of energy that the country has, 1988 million barrels of oil, 7277 Giga feet of natural gas, 6 667 million tons of coal and 93 GW in hydropower are used as data.

4.2.4. Scenario simulation

In order to structure the possible scenarios, a detailed analysis of the current situation with a time perspective of 25 years, having 2030 as its final year, creating situations that could be present in the near future, applying concepts for sustainable development and variability, climatic vulnerability and sensitivity, observing the geographic location Intertropical Convergence Zone (ITCZ) where Colombia is located.

The year 2005 was set as reference under the criteria that it is not an atypical year in energy consumption; it does not presents abnormal situations such as El Niño Southern Oscillation ENSO or shortfalls in energy supply. The sources of energy supply and economic data were consolidated and available, especially the energy balance, manufacturing and household surveys, national accounts and gross domestic product by industries.

Three fundamental simulations are considered for scenario conceptualization, two are focused on simulating the demand with the demographic and Gross domestic product (GDP) growth scenario, and the rational and efficient use of new energetic. Secondly, great simulation based on the historical series of events from the last fifteen years take into consideration the electrical power supply, based on the expansion in generation plan, which for the first time it makes a simulation of the electrical production with the presence of a climatic phenomenon, specifically the El Niño Southern Oscillation ENSO, and varying the contributions of flows entering reservoirs.

Baseline scenario was comprised with a vegetative population growth, according to the population projections provided by the DANE and insights on the normal tendency of energy consumption; this scenario is denominated population increase and demand, in which simulations are done in three stages as follows:

4.2.4.1. Demographic and demand growth. Demand scenario without energy efficiency policies, there is no substitution or participation of new energy and only having the vegetative population growth and Gross domestic product (GDP).

4.2.4.2. Energy rational use, new energy and energy efficiency. The plan for energy's rational use (PROURE) from the UPME [42], the new energy for some demand subsectors (which will be specified and justified in each section) and an increase in the technologies energy efficiency will be considered.

4.2.4.3. Expansion in generation and climate phenomenon. This scenario is cataloged as a simulation of the electric energy supply, based on the [43], UPME, Plan de Expansión de Referencia en Generación y Transmisión 2010–2024 associated with a generation obligation scenario but under a new component denominated *El Niño* Southern Oscillation ENSO and an integral analysis is made with each technology, including renewable, under this assumptions. Renewables behavior introduction in the energy matrix is analyzed, under *El Niño Southern Oscillation ENSO*; coal and natural gas power plant supply functioning gets examined.

4.3. Renewable energy alternatives selection and combination ENERSOS

In the Colombian case study, the model starts starts from the identified energy potential in the ENERGIS module. The obtained results were wind energy, solar energy and biomass and with base on these the existing energy technologies in the market were identified. Subsequently, the alternatives were selected for the application of the VIKOR method to the case study (Table 1).

These alternatives A_j, were evaluated according to the six attributes, f_i, which were considered to be more representative for the Colombian energy sector (Table 2) and are referred within the three sustainability dimensions; even though, ENERSOS allows for the introduction of new attributes according to the decision maker's preference

A matrix called "Payoff Matrix" was built (Table 3) which indicates the performance of each alternative against each criterion, in order to present all the information that the user has during the decision making process.

First the calculation for ranking technologies through the multi-attribute method, these results are later used to optimize according to the Multi-objective VIKOR method which gives as result the optimal combination of technologies that power once again ENERDEM scenarios.

Table 1
Renewable alternatives for electricity generation.

A_j	Alternative
A_1	Wind Energy
A_2	Solar Thermal Energy
A_3	Photovoltaic Solar Energy
A_4	Wood Energy Biomass
A_5	Co-combustion/ Biomass

Table 2
Selected criteria to evaluate alternatives.

f_i	Criteria	Unit
f_1	Output	KWh/year
f_2	Investment per installed power	\$US/KW
f_3	Implementation time	Years
f_4	Useful life	Years
f_5	Non-emitted CO_2	Tons/year/KW
f_6	Land use	Ha/KW

Table 3
Payment Matrix: Alternatives and Evaluation criteria.

Alternatives	Criteria					
	f_1	f_2	f_3	f_4	f_5	f_6
A_1	61 320 000	1580	1	20	873.50	0.00204
A_2	87 600 000	3082	2	25	1247.86	0.00219
A_3	52 560 000	3823	0.5	25	748.72	0.00100
A_4	87 600 000	1886	1	15	623.93	0.00450
A_5	87 600 000	1886	1	20	623.93	0.00390

The chosen alternatives are technologies that generate renewable energy from which one or various will be selected to enhance the renewable energy participation in the national "energy mix." The method VIKOR consists of a series of steps explained in detail by its author [22], reason from which some calculations are omitted to get to the point of interest, leaving an open possibility for the user to enhance the method when needed.

4.3.1. Multiatribute analysis

Step 1 Selection:

Since VIKOR is characterized as a method based on distances, the best and worst values corresponding to each criteria are searched for in order to evaluate the alternatives with respect to these. The best values are definedf_i^*, and worst, f_i^-, for each of the criteria (Table 4). If the i-th function of criteria represents profit then $f_i^* = max f_{ij}$ and $f_i^* = max f_{ij}$

Step 2 Value Determinations S_j andR_j:

S_j and R_j Values are determined through (1) and (2) respectively. $S_{j,}$ represents the distance of the alternatives to the best solution and $R_{j,}$ represents the distance between the alternatives and the worst option.

$$S_j = \sum_{i=0}^{n} w_i \left[\frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \right] \tag{1}$$

$$R_j = max_i \left[w_i \frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \right] \tag{2}$$

w_i is the given weight to criteria i, expressing the preference of the decision makers as the relative importance of the criteria. These weights can be adjusted by using AHP [22].

(a) Finding the relative importance from different attributes with regards to the objective. To do this, a comparison matrix among pairs using a relative importance scale is build. The trials are emitted taking into account the fundamental AHP scale. An attribute compared to itself will always have a value of one; therefore, the matrix's main diagonal shall consists in its entirety by the number one. Numbers 3, 5, 7 and 9 correspond the verbal judgments "moderate importance, "strong importance," "very strong importance" and "absolute importance." Assuming n attributes, the comparison between pairs of i attributes with j attributes generates A_{nxn} matrix where a_{ij} denotes the comparative importance of i attribute with respect to j attribute. In the matrix, $a_{ij}=1$when $i=j$ and $\alpha_{ji}=1/\alpha_{ij}$.
The realized adjustments are presented on the table as illustrating purposes for a better comprehension of the case study (Table 5).

(b) Obtaining the vectors of weights. The vector $W=[w_1, w_2, \ldots, w_n]$ is obtained by normalizing the adjustment matrix A,. For each A column, divide each entry in column i by the sum of all entries of the same. This leads to a new matrix, called A_{norm} in which, the sum of all entries in each column is one. $w_i$is estimated as the average number of entries in the row i ofA_{norm}. The calculated weight for the case are $w_1=0.1465$; $w_2=0.2275$; $w_3=0.0838$; $w_4=0.1227$; $w_5=0.1227$; $w_6=0.2968$.
$W=[w_1, w_2, \ldots, w_n]$ Vector is obtained through the normalization of the adjustment matrix, A, procedure that can be consulted in any referent material to AHP [44]. The calculated weights for the case are $w_1=0.1465$; $w_2=0.2275$; $w_3=0.0838$; $w_4=0.1227$; $w_5=0.1227$; $w_6=0.2968$.

Table 4
Maximum and minimum values of evaluation criteria.

	f_1 Max	f_2 Min	f_3 Min	f_4 Max	f_5 Max	f_6 Min
f_i^*	87 600 000	1580	0.5	25	1247.86	0.00100
f_i^-	52 560 000	3823	2	15	623.93	0.00450

Table 5
Adjustment of attributes using the AHP method.

f_i	f_1	f_2	f_3	f_4	f_5	f_6
f_1	1	1	3	1	1	0.333
f_2	1	1	1	3	3	1
f_3	0.333	1	1	0.333	0.333	0.333
f_4	1	0.333	3	1	1	0.333
f_5	1	0.333	3	1	1	0.333
f_6	3	1	3	3	3	1

Table 6
Q_j, S_j y R_j calculated values with $\nu=0.5$ for the alternatives.

A_j	A_1	A_2	A_3	A_4	A_5
S_j	0.3102	0.5492	0.2447	0.7217	0.6290
R_j	0.0881	0.2274	0.1465	0.2967	0.2458
Q_j	0.0686	0.6531	0.1398	1.0000	0.7808

Step 3 Calculation Calculate Q_j, Q_j, Values through (3). This expression is the aggregation function feature of the method that measures the distance of the alternatives to the ideal solution, taking into account the distance to the best and worst solution (Table 6).

$$Q_j = \left[\nu \frac{(S_j - S^*)}{(S^- - S^*)} \right] + \left[(1-\nu) \frac{(R_j - R^*)}{(R^- - R^*)} \right] \tag{3}$$

$S^* = min_j S_j$; $S^- = max_j S_j$; $R^* = \acute{m}\acute{\imath}n_j R_j$; $R^- = max_j R_j$ and ν is introduced as the value that represents the decision-makers' position towards risk. Usually the value of ν is taken as 0.5 to represent a neutral position against risk; even though, it can take any value between 0 and 1.

Step 4 Ranking alternatives:

Ranking alternatives is organized according to the values of S, R y Q in descendent order. The results obtained are three ordered lists. It is intended as a compromised alternative to $A^{(1)}$, which is the best of them all according to Q (minimum) measurement, if a) and b) conditions are meet as follow:

(a) Acceptable advantage: marks to $Q(A^{(2)})-Q(A^{(1)}) \geq DQ$, where $DQ=1/(J-1)$y $A^{(2)}$ is the alternative that occupies the second position in the ordered list for the value of Q.

(b) Acceptable stability: It is satisfied that alternative $A^{(1)}$ shall also be the best on the$S$and/or$R$ lists.

If one of these conditions is not satisfied, then it proposes a series of compromise solutions, which consists of:

(c) $A^{(1)}$y$A^{(2)}$ Alternatives only if b) condition is not satisfied.

(d) $A^{(1)}$,$A^{(2)}$,…,$A^{(m)}$Alternatives if a) condition is not satisfied. $A^{(m)}$is determined by the relation of $Q(A^{(m)})-Q(A^{(1)})<DQ$ for maximum n.

Once the best alternatives are selected, one can opt to refine the options even more in order to elaborate more realistic projects. A novel method is proposed for developing ENERSOS an algorithm that finds all possible combinations of the best alternatives compiled by the previous method. What is sought is to obtain the optimal combination by using a modified VIKOR method to resolve a multi-objective problem subject to a restriction, which for the case development is the capacity to change the energy matrix.

4.3.2. *Multi-objective analysis*

The multi-objective method VIKOR is used to determine the best combination of the renewable energy alternatives, and obtain a required energy capacity to equilibrate the energy matrix, by increasing the participation of renewable energy sources. In order to start, a multi-objective planning of the problem must be done [28], beginning with the objective functions, in other words, build a set of functions to describe targets in various aspects.

Step 1: Objective Functions Definition

In the description of the objective functions, Z_i, one or more factors are involved influencing the achievement of these goals (Table 7). These factors are called attributes, z_i, also they can be expressed as functions of the unit quantity that corresponds to each alternative: Z_1,Z_2 y $Z_3$are functions of x_1,x_2,x_3, variables respectively expressing the number of unit generation of energy alternatives that want to be implemented.

In turn, the objective functions are functions of attributes, which are also functions of x_1, x_2, x_3

Step 2: Restriction Definition

(a) The sum of the powers of the number of units from the different alternatives generation should be equivalent to the required power

$$P=200000x_1+20000x_2+20000x_3 \tag{4}$$

(b) $P=200000x_1+20000x_2+20000x_3$ x_1, x_2, x_3 must be a positive integer.

Step 3: New Alternatives Acknowledgment

The best three alternatives were obtained from the multi-attribute approach. In the multi-objective approach new alternatives will be defined as each of the possible combinations of the above alternatives that meet the predefined restrictions.

The algorithm used to generate these combinations consists on entering a restriction to limit the output power of the combinations. A series of iterations are to give values to three variables and check the condition each time. If the condition is meet it is stored in the matrix. If the condition is not meet, the program continues with the next combination and keeps progressing until no more possible combinations are found.

Step 4: Payment Matrix Generation

If A_i equals the value combination i and n equals the number of combinations number of alternatives to evaluate, then the payment matrix is generated through the evaluation of each alternative in each attribute role A_i (Table 8).

Step 5: AHP Adjustment Criteria

The criteria are classified on two levels. The first corresponds to the economic, environmental and social objectives. The second level corresponds to the attributes from which each objective depends. The same procedure [29] is continued to find the weights each objective has. In this case an importance five times greater is given to the economic and environmental objectives than to the social objective. After acquiring the corresponding weights, each objective's interior was compared; i.e. for the economic objective attribute 1 was compared with attribute 2, giving an importance of 1 for both attributes. For the environmental objective attribute 3 was compared with attribute 4, which were given an importance of 1. The weight obtained after completing the procedure: $w_{z_1}=0.2272$; $w_{z_2}=0.2272$; $w_{z_3}=0.2272$; $w_{z_4}=0.2272$; $w_{z_5}=0.0909$.

Table 7
Objective Functions Definition.

Z_i	Objective	Description
$Z_1=f(x_1,x_2,x_3)=z_1+z_2$	Economic	Greater electric generation at a lower economic investment
$Z_2=g(x_1,x_2,x_3)=z_3+z_4$	Environmental	Generate the least negative impact on the environment. High CO2 emissions avoided, minimum land use
$Z_3=h(x_1,x_2,x_3)=z_5$	Social	Give the greatest benefit to the community. Maximum number of jobs created

Table 8
Attribute Functions Definition.

z_i	Attribute	Mathematical Expression	Units
z_1	Cost per installed power	$31600000x_1+76460000x_2+61640000x_3$	\$US/kW
z_2	Generated Power	$61320000x_1+52560000x_2+87600000x_3$	KWh/year
z_3	Non-emitted CO2 emissions	$17470060x_1+14973340x_2+24957200x_3$	Ton/kW/year
z_4	Land Use	$40.8x1+20.0x2+43.8x3$	Ha/kW
z_5	Jobs Created	$20x1+20x2+40x3$	Number (#)

Table 9
VIKOR multi-objective method first three results.

	$A^{(1)}$:(30,37,33)	$A^{(2)}$:(29,37,34)	$A^{(3)}$:(28,36,36)
Q_j	0.2807	0.2808	0.2813
R_j	0.1352	0.1358	0.1374
S_j	0.6002	0.5977	0.5913

Table 10
Potential Summary with MODERGIS.
Source: ModerGIS.

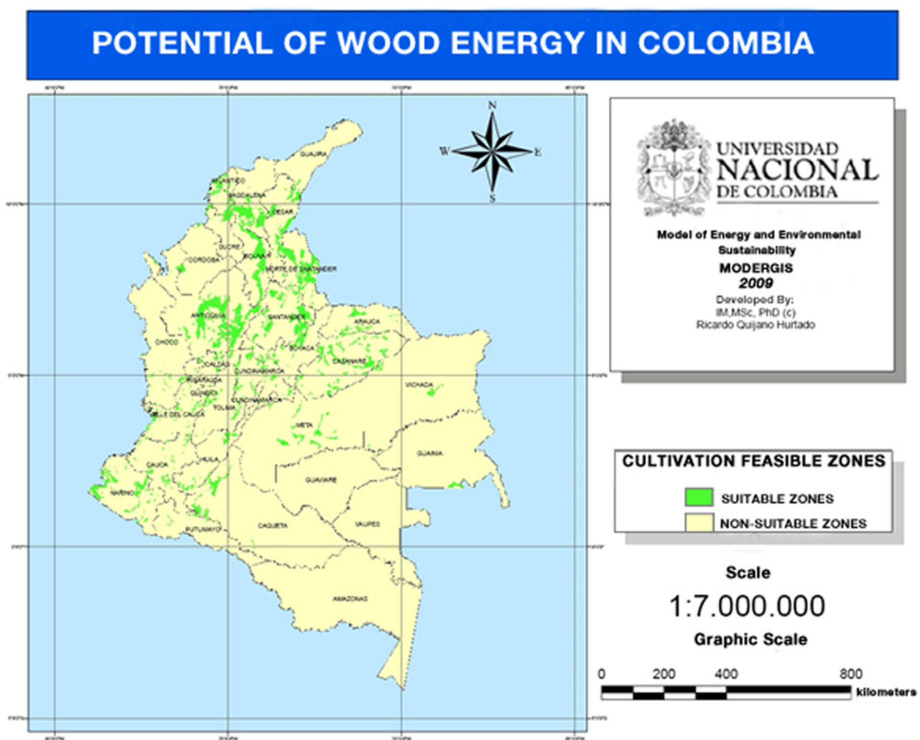
Source	Unit	Potential Capacity	Characteristic
Solar Energy PV	GW	349.4	Just (1%) from the achievable 30%
Wind Energy	GW	26.6	High Power (1300 Kw)
Wood Energy	km^2	68 066	Forest Biomass (Sustainable)
Oil Palm	km^2	291 486	African (Sustainable potential)
Sugar Cane	km^2	9 667	Sugar Cane (Sustainable potential)
Banana	km^2	134 823	Banana (Sustainable potential)
Corn	km^2	61 860	Corn (Sustainable potential)
Jatropha	km^2	710 619	(Sustainable potential)

Step 6: VIKOR Method Application

The same previous planned steps for each of the found combinations by the internal proposed algorithm are needed in order to apply the multi-objective method VIKOR. The expected result is an ordered list of all combinations where the best ones are indicated according to the preferences of the decision-maker. The restriction of power input for the case study was 20 00 MW and the program showed 5151 combinations from which only the first three combinations with its respective values of Q_j, S_j y R_j.will be shown, (Table 9).

5. Results and analysis

MODERGIS results are the potential sources of renewable energy, starting from the environmental zones, social and culturally are feasible for sustainable use, it is shown in Table 10, that 26634 MW of wind power potential was identified, 349,4 GW solar power potential, much more superior to the one presented by the European Solar Panel manufacturer association EPIA, whom report 5900 MW, due to the fact that their references are based on the country's capital radiation, in this case Bogota. Biofuels



DEPARTMENT	Has potentials	Potential Mw	DEPARTMENT	Has potentials	Potential Mw
ANTIOQUIA	1.256.050	733	HUILA	516.000	301
ARAUCA	56.975	125	MAGDALENA	19.800	17
ATLANTICO	237.725	139	META	5.750	13
BOLIVAR	648.275	378	NARIÑO	602.025	351
BOYACA	200.325	117	NORT/SANTANDER	41.000	24
CALDAS	74.750	44	PUTUMAYO	150.175	88
CAQUETA	230.225	134	QUINDIO	143.300	84
CASANARE	140.650	309	RISARALDA	165.175	96
CAUCA	355.125	133	SANTANDER	497.075	290
CESAR	40.450	24	SUCRE	34.075	20
CHOCO	90.075	53	TOLIMA	44.300	26
CORDOBA	126.025	109	VALLE/CAUCA	1.575	1
CUNDINAMARCA	19.725	12	VICHADA	84.775	182
GUAINIA	393.150	230			
GUAJIRA	233.350	136	TOTAL	6.806.600	4.401
GUAVIARE	398.700	233			

Fig. 2. Potential Wood Energy Map in Colombia.
Source: ModerGIS.

contributed 9667 Km^2 for sugar cane in bio-alcohol production, 291486 Km^2 in African palm, to mix diesel oil and to produce biodiesel and 366310 Km^2 for forest biomass, which could be used in co-cogeneration plants or third generation biofuels.

In addition to the figures presented by MODERGIS the program has the easiness of creating maps that can be present in a regional or local manner its potentials for doing more accurate analysis. In this sense the potential of wood energy in Colombia mas is presented as an example. The map displays 6.8 million hectares developed by each of the departments, which means that the analysis can be done at the departmental and municipal level of any of the processes sources (Fig. 2). It clearly shows that the Orinoco, Amazon and Choco areas were excluded, respecting the criteria for sustainability. However, there is significant potential that could be used to develop biofuels from wood or for second and third generation biofuels without entering into conflict with the protecting sensitive areas or from indigenous or African descent communities.

The effect that El Niño Southern Oscillation ENSO could have with the hydro-thermal system from the national electric system was simulated. It is observed that there would be a supply deficit after the year 2020, since the thermal park is limited by the capacity of its plants and cannot surpass 5000 GWh year in coal and 20 000 GWh year in natural gas.

As energy demands, the obtained results by the MODERGIS simulation, presents some requirements of total energy demand for the year 2030 of 1707 400 TJ, and 249430 TJ in electricity. In power generation 87416 GWh are required as provided in the expansion plan. In what is simulated with this model and scenario of the *El Niño Southern Oscillation ENSO* will only be on the order of 80510 GWh. The difference is not provided for in the UPME expansion plan which embodies the possibility of change in the power matrix of moving from 0.2% to 7% proposed by this research stage scenario of El Niño Southern Oscillation ENSO, to correlate for the flaws.

It is clear that the scarcity of water resources or water in the hydroelectric (Fig. 3) is reflected in the increase of fossil fuels and satisfies the demand for energy, incrementing the consumption of Natural Gas and coal ore, and the most importantly we notice how the participation of wind and solar energy increases when El Niño Southern Oscillation ENSO is present.

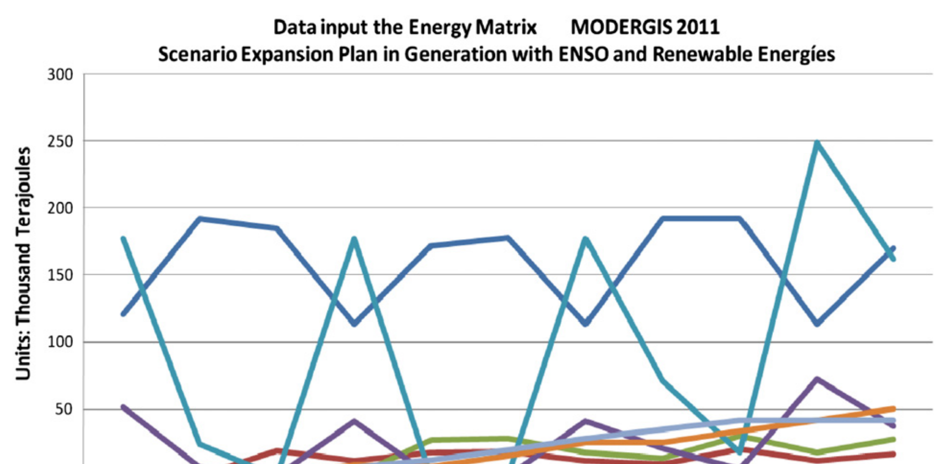
Power forecasts for the year 2030 are of 87416 GWh according to the ENERDEM Expansion in generation plan. In the same way what was simulated in the *El Niño Southern Oscillation ENSO* scenario will be around 80,510 GWh. The difference not foreseen by the UPME generation expansion plan represents a difference of 6906 GWh/year that in power would mean an additional 1200 MW facility to overcome the deficit that would be endured as a result of *El Niño Southern Oscillation ENSO*. This additional power would be offered with solar and wind renewable energy, which constitutes a 7% of the planned capacity for the expansion plan of 16943 MW. In this sense, MODERGIS meets the objective of proposing a change in the percentage share of renewables in the "energy mix," going from 0.2% to 7% to meet the deficit, thereby ensuring the sustainable supply of electric energy.

In order to overcome the shortage of 1200 MW, ENERSOS presents three optimal combinations for a power offer of 2000 MW; a first combination of 30 Wind power generating units, 37 Photovoltaic solar energy generating units and 33 Thermoelectric Solar energy generating units, all of 20000 KW. A second combination formed with 29 Wind power generating units, 37 Photovoltaic Solar energy generating units and 34 Thermoelectric Solar energy generating units, of 20000 KW. A third combination of 38 Wind power generating units, 36 Photovoltaic Solar energy generating units and 36 Thermoelectric Solar energy generating units of 20000 KW.

6. Discussion

One contribution of this model is to enhance the versatility of renewable and sustainable energies in an economic way by optimizing the use of information and computational resources within the local and regional scheme.

The second contribution of this model is the flexibility within the simulation scenarios, which present alternatives of change for a more sustainable energy mix and equitable according to the



	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
hydro power Interconected System	121	192.4	184.5	113.1	172.1	177.7	113.2	192.4	192.3	113.2	169.8
hydro power Sogamoso	0	0	19.3	11.9	18.1	18.6	11.9	9	20.2	11.9	16.3
hydro power Pescadero	0	0	0	0	27.1	28	17.8	13.5	30.3	17.8	27.6
Thermo power Coal Inter Sys	51.7	7	0	41.4	0	0	41.4	20.7	5.2	72.4	37.8
Thermo Power Natural Gas Inter Sys	177.5	24.2	0	177.5	0	0	177.5	71.1	17.8	248.6	162.1
Wind Power MODERGIS	0	0	0	8.4	7.5	15.5	25.2	25.2	33.6	42	50.5
Solar PV MODERGIS	0	0	0	7	12.5	19.4	28	35	42	42	42

Fig. 3. El Niño Southern Oscillation ENSO Simulation in Colombia.
Source: ModerGIS.

available resources of the region including environmental issues and their consequences on the reliable supply of energy.

The third factor is the possibility of renewable and sustainable energy by developing plans for expansion of these energies, taking into account critical environmental conditions and promoting the use of available resources.

It is important to highlight that the reliable and adequate supply of the information could be a limitation on the use of MODERGIS especially cartographic information, but many alternatives are available to achieve preliminary information that may lead to approximate results of high reliability.

7. Conclusions

The model achieves its goal of identifying the potential of renewable and sustainable energy, like solar power, wind power generators and crops, with the use of secondary information and without the installation of measurement equipment, with very successful results and sustainable criteria.

Select the best alternatives to meet energy restriction generated by the El Niño Southern Oscillation ENSO, which is the change in the energy matrix to the inclusion in renewable power generation of 0.23% share in 2005 to reach exte7% in 2030 using two alternative solutions, wind and solar energy installation with a margin of 2,000 MW.

ENERSOS as a contribution to the model conceptualizes and builds an algorithm to determine a plan for renewable energy sources, given a restriction given in MW. This algorithm is based on translating combinations of renewable energy alternatives, taking data from the results in the ranking of VIKOR multi-attribute method under the constraint of MW power, which indicates how much is the change in the participation of the national "energy mix" with renewable energies, attempting to solve a problem which constitutes the lack of energy in terms of rainfall to reservoirs, variable not simulated in traditional models.

MODERGIS analyzed the implications that result from simulating a climate variable, such as the El Niño Southern Oscillation ENSO and its impact on the entire energy system, opening spaces for renewable energy and sustainable sources with sustainable vision so that renewable resources can be incorporated in the energy plans in the medium and long term. Thus it is observed that existing natural gas reserves, after 2018, would be presenting a critical level of depletion in relation to the established demand, particularly electricity generation. This problem could be overcome with sources of renewable energy such as wind, solar and co-combustion, supplemental plan results in the renewable resource and energy entered into the energy mix, for MODERGIS.

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